In My

Judgment

by Adam Neville

A Challenge to Concretors

Just because concrete is a highly successful and the most widely used construction material, there is no guarantee that it will continue indefinitely to keep its preeminent position. Life is competitive, and there needs to be continual progress and change. This article is a deliberate provocation to help foster an evolution in concrete practice.

Change has to be rooted in research. I recognize that much research in the field of concrete continues to be undertaken, but is it always being accomplished in the right place and by the right people? In the past, much research work was performed, at least in some countries, in government research organizations, and in trade association laboratories. For example, in the United Kingdom, in the half-century starting in the 1930s, considerable progress was achieved by bodies such as the Building Research Establishment, the Road Research Laboratory, and the Cement and Concrete Association. This is no longer the case.

In the U.K., in consequence, the bulk of research on concrete is performed in universities. Now, universities, with their departmental organizations and with their emphasis on personal achievement and its related individual promotion, inevitably encourage an ever-narrowing specialization by individual researchers. I am aware of the fact that interdisciplinary centers are encouraged, but there have not been many success stories of materials specialists and structural engineers *jointly* developing better concrete structures *in practice*.

Specialists

The preceding statement is not a criticism, but rather a recognition of the fact that the complexity of structural engineering *and* of concrete as a material, with its numerous and varied ingredients, is beyond the capacity of a small research group, let alone an individual. The consequence is a greater specialization by individual professors. Though individual circumstances do differ, it is conceivable that a professor may spend a whole life at one and the same university and also has spent it working on a single subject, possibly a continuation of a PhD topic. The professor may have moved through all the professorial ranks, even beyond a Full Professor to a Distinguished Professor.

This professor might have become an outstanding specialist in a narrow field, which over time may continue to be of importance. This work is useful and valuable. It is valuable to other engineers who deal with structures, their design and construction. They turn to the professor or other authority for specialist advice, but he or she might not advise radical changes in the design that would remove a systemic problem.

Let me hasten to emphasize that specialists are, of course, needed. There is also the difficulty of there being fully competent generalists who know enough about design, construction, and materials. But, the designer should know enough in order to know what is possible and what advice is needed.

This situation is not limited to structural engineering; it can even be more severe in other disciplines, for instance medicine. A friend of mine recently had serious problems with his cardiovascular system—and at his somewhat advanced age, this is almost a *déformation professionelle*. Upon a specialist's advice, he had to undergo major heart surgery. All went well, because these days the heart surgeons are extremely competent and are supported by excellent technology devised by engineers who, in the eyes of the public, tend to be nameless and faceless. However, upon his return home, my friend became, in his words, “very anemic.” He was rushed back to the hospital where a consultant in internal medicine discovered a very old and neglected duodenal ulcer. When this was cured, my friend felt “fighting fit” for the first time in years. Why this dreary story? We live in days of high specialization, with generalists hardly in existence. Even a general medical practitioner, as soon as he or she identifies a particular problem, refers the patient to a specialist who never looks outside of his or her field of knowledge and thus can miss much.

Generalists

The extent of specialization is necessitated by the explosion of knowledge and the impossibility today of knowing much beyond the narrowest of fields. I was familiar with a number of people who were civil engineers by training, with a continuing interest in real-life construction: Eduardo Torroja in Spain, Hubert Rüsch in Germany, Bob Philleo in the U.S.; they are gone now. There probably are a number of such people still alive, but the only ones whose names spring rapidly to mind are Pierre-Claude Aïtcin and Mohan Malhotra in Canada, and Chester Siess in the U.S.

I think that a critical characteristic of these people is that they were trained as civil or structural engineers and had their roots in engineering. They may have not learned much about concrete at the university (I had a total of nine lectures in my degree course), but later they could acquire the necessary knowledge of materials. I believe that, with good grounding in engineering and a knowledge of chemistry and physics acquired as a part of their engineering courses, they knew the essentials and they knew enough to know what to seek from specialists. The converse is not true: a chemist, a geologist, or a materials science graduate is most unlikely to acquire *on the job* an adequate knowledge of structural behavior, let alone structural analysis.

In case the reference to structural analysis causes raised eyebrows, let me mention the consideration of creep in the design of reinforced and prestressed concrete structures. I have met some designers who can only use a few standard coefficients to allow for creep in their analyses, and who are not sufficiently aware of the influence of the composition of concrete upon creep. At the other extreme, there are creep specialists whose main preoccupation is with developing elaborate, or even extremely complex, formulae that describe creep in laboratory specimens. They, however, do not seem to concern themselves with the behavior of structures in service, in which the stresses are far from constant over time, and in which creep recovery as well as relaxation occur. Of course, people whose knowledge spans both creep of concrete as a material and of the variable and multiaxial stresses involved in a structure do exist. Two examples are Walter Dilger and Amin Ghali, both in Calgary.

What I have described so far are examples of what I see as root problems in concrete, but what is more important, they underlie the recurrent problems with concrete structures in service. It is extremely rare that such structures collapse, and this is a tribute to structural designers. There is, nevertheless, an inherent problem in design, and this is the economic consequence of an excessive variability of concrete. By the term “excessive” I mean that a reduction in variability would lead to economy, and I propose now to discuss the main reasons for variability of concrete as produced nowadays.

Safety factors

Modern structural design involves a probabilistic assessment of safety. With respect to concrete, the characteristic strength of standard test cylinders or cubes is, so to speak, converted into the service strength of concrete in the structure by a partial safety factor for material. Such factors vary between different design codes, and I shall limit myself to the example of the British code for structural concrete. First of all, I wish to consider the partial safety factor for strength: the design strength is the characteristic strength of concrete divided by this factor. According to the 1972 British code, the rationale of the partial safety factor for the strength of materials is “to take account of possible differences between the strength of the material in the actual structure and the strength derived from test specimens.” The 1985 code explains that the partial safety factor for the strength of materials “takes account of differences between actual and laboratory values, local weaknesses, and inaccuracies in the assessment of the resistance of sections.” As I was a member of the committees drafting both of these codes, I have to accept the above statements as being correct.

The value of the British factor for concrete is 1.5; by contrast, the value for steel is 1.15. This difference between the two materials is striking, and it reflects that steel is factory-produced, with actual coupons of some steel rods tested for yield stress and for extension. On the other hand, concrete is placed, compacted, cured (or not cured), and treated (or mistreated) by concretors on site. This is not all. What is often forgotten is that this partial safety factor of 1.5 is applied to the characteristic strength of concrete. The characteristic strength allows for 5% of the standard cylinder strengths being too low (but not too much so) so that the value used in design is well below the mean strength of the cylinders. In other words, 95%

of the cylinder strengths are greater than the value of strength that is subjected to the partial safety factor for the material.

Variability of concrete strength

I presume it is not necessary to explain that the difference in the values of the mean strength and the characteristic strength is a reflection of the scatter of the strengths of the test cylinders. The scatter is expressed as the standard deviation. For a value of characteristic strength of 5%, the abscissa at that strength, reckoned from the mean strength in the normal distribution, is equal to 1.64 times the standard deviation. Now, the concrete mixture has to be designed on the basis of the *mean* strength. It follows that any reduction in the difference between the mean strength and the specified (and achieved) characteristic strength represents an economic gain because a smaller proportion of test cylinders has what might be termed an excessive strength. Because the difference is 1.64 times the standard deviation, a reduction in the magnitude of the standard deviation is clearly beneficial.

I strongly feel that a reduction in this "difference" when achieved in practice will represent the greatest economic benefit for concrete. I see this as far more important than obtaining a higher characteristic strength. And yet, as far as I know, apart from internal work by ready-mixed concrete producers, this "difference" is not being researched. Why? Because such work cannot be done in the laboratory, but only on site, dealing with "real materials" as they exist in place and with actual site procedures.

The point that I am trying to make is that there is a large difference between the strength of concrete called for to satisfy the structural design requirements and the strength that the ready-mixed concrete plant must produce to allow for the variability of the mixture as it leaves the mixer. Also, there is the fact that the processing on site is far from perfect. I am not saying that this difference is not necessary: it *is*, because safety is paramount. But, it is vital only because the procedures both of batching and of site operations are such as they are. To put it bluntly and generally, these could be much better. More to the point, if they do not improve, concrete is likely to lose ground to other construction materials.

Doing better, then, means reducing the scatter of strength of concrete coming out of a mixer and also improving site treatment so the difference between the *potential* strength of concrete and its *actual* strength in situ is reduced. Only then can we produce concrete more economically without sacrificing safety.

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Possible improvements in concrete

The question then is: how can we do better? I am not competent to write a recipe, but I can identify a few areas in which improvement is possible. Let me start with mixture ingredients.

One source of variability of concrete at the point of discharge from the mixer is variability in aggregate grading. I know that aggregate is screened into several size fractions, which are combined in the batcher. But each size fraction covers a fairly large range of sizes, and *within* a specific range it is possible to have different grading. For example, in the fraction comprising particles 10 to 20 mm (3/8 to 3/4 in.) it is possible to have more or fewer particles nearer the smaller size. If there are more small particles present, the water demand is likely to be greater or the workability lower. As workability *must* be as specified (otherwise the concrete cannot be consolidated with the means foreseen and provided on site), the ready-mix plant must provide for the worst scenario. The influence of precise grading of the finer fraction of fine aggregate is even greater, and sometimes there is large variation in the grading of the finest particles. This means that, not to compromise the characteristic strength, the average strength has to be higher than would be the case with a much more closely controlled grading. Aiming at a higher *average* strength represents, of course, a higher cost and makes concrete more expensive than could be achieved with a better control of aggregate and the moisture it contains.

The same argument applies to the presence of flaky or elongated particles of coarse aggregate. The usual controls are on the maximum proportion of such particles, but the actual proportion may be much lower. However, the design of the mixture must allow for the worst situation, which may be rare—but nobody knows when it will occur. This is especially so when the aggregate is supplied from more than one crusher. On an earlier occasion, I described a situation when one crusher was badly worn and consequently delivered aggregate with a significantly different shape from the other, but newer, crushers. The differences in the surface texture of the aggregate play a similar role with respect to the variability in the workability of the concrete coming out of the mixer. Physicists are able to measure the texture of particles, and we should endeavor to apply such techniques to aggregate as actually batched.

Still on the topic of variability of aggregate, there is the vexing problem of its moisture content. This varies notoriously, and usually the determination of moisture content is sporadic and infrequent. Determination of the *real* amount of water in *every* individual batch of aggregate as it enters a mixer is rare. In any case, I for one have not seen evidence of the reliability of such a determination coupled with an automatic adjustment of the amount of added water on a batch-by-batch basis. The point that I am trying to make is that if *precise* grading of aggregate, an assessment of its shape and texture, and measurement of moisture content were made on a batch-by-batch basis, then a considerable reduction in the variability of concrete coming out of the mixer could, indeed would, be achieved. This would lead to economy, but of course only after the cost of developing the new methods has been amortized.

As far as the development of a much better control of aggregate grading and shape is concerned, I think there is an additional factor at play, namely the use of recycled aggregate. Unless such aggregate is "good" and has well-controlled properties, there will be difficulties in its use. And yet we must use more and more recycled material. In many areas, sources of natural aggregate are running out or are conserved by legislation. Moreover, in a number of European countries, natural aggregate is subject to fiscal measures. Also, the use of a specified minimum proportion of recycled aggregate is mandatory. In the United Kingdom, during the last decade of the twentieth century, the sales of crushed rock, gravel, and sand, taken together, fell by 30%. In 1999, aggregate from other sources represented 18% of the total market. The other sources are: processed demolition material, used railway ballast, incinerator bottom ash, slag, slate waste, and other waste products. What is needed is the means of measuring precisely the properties of these aggregates.

The feeling of many people involved in the production of concrete is simply: this is how it is. They have little interest in achieving a closer control of aggregate characteristics, and even less interest if the source of aggregate belongs to the ready-mix concrete producer. A righteous, but perhaps naive, person might ask: why not? The answer is that such improvements would require a great deal of money and, in the short term, their costs would outweigh the economies gained.

A friend of mine, who is a prominent and highly successful concrete entrepreneur, once explained to me: "As long as everybody else does equally badly, there is no benefit in spending money to do better."

Of course, this is true, provided the customer *must* buy concrete because there is no alternative material that could be used. I shall come back to this later.

Ecological considerations

With a tight control of aggregate grading, there would also be a reduction in concrete wasted because it has been rejected for want of adequate workability or because of other deficiencies. Economy would lie in less cement being used, and this would please those preoccupied with ecological considerations and the popular concept of sustainability. Of course, we should reduce the emission of carbon dioxide into the atmosphere, but is concrete really a significant culprit? For instance, at the risk of offending many people, I cannot refrain from commenting on the use of motor cars. One example: on Californian freeways, for every car in the pool lane (obliged to carry at least two people) there are probably 10 cars that fit the description "one car, one person." Maybe the current car usage in California and elsewhere is essential for the comfort and well-being of people living there, but if we are serious about reducing noxious emissions, we should press on with cars and not with concrete. In comparison, to concentrate on concrete can be likened to reducing the price of caviar by using cheaper wrapping.

Possible improvements in site work

On site in some countries, concrete construction suffers grievously from the poor education and technical skills of the local operatives. There is, at present, little incentive to employ more highly skilled labor, even if they could be found. Such people would naturally and justifiably have to be paid more, but many contractors are shy of such expenditure. Again, it is a situation where there is no incentive to do better than your competitors. On other occasions, I have suggested that the solution to this problem lies in a mandatory provision in contracts to employ a proportion of trained and certificated operatives and tradesmen. To begin with, this could be done in construction for government agencies. Once contractors employ better-skilled people for these contracts, they would find such labor beneficial, albeit more highly paid, in construction projects for other clients as well.

It is also possible to reduce the overall number of people required for concrete construction. In the March 2001 issue of *Concrete International*, authors P. Kumar Mehta and Richard W. Burrows stated: "Globally, we do not have a labor shortage." But such laborers are not skilled concretors, and they would perpetuate the existing system. Moreover, to move these people around the world to the highly industrialized areas needing them would be a modern equivalent of the indentured labor once employed in sugar, tea, and coffee plantations in the bad old days. Rather, I believe that the solution lies in the use of robots and in a much greater mechanization of concreting. Some mechanization, but not enough, exists in highway construction. Much progress, especially in the use of robots, has been made in Japan, a country opposed to importing foreign labor. Moreover, with a very large proportion of the population of Japan educated to university level, there are few of its people keen to work as concretors.

As I have said earlier, this is not the occasion for suggesting specific remedies, and I am not qualified to develop them. Many technologies existing in other fields of endeavor could be applied fairly readily, for example, to classify aggregate and to determine its shape and texture. Of course, all this takes money, but, in the long run, it would ensure that concrete will continue in its preeminent position as a construction material.

My frequent trips abroad had to do with the investigation of problems, real or alleged, with concrete and concrete structures. Much effort, time, and money are devoted to the resolution of such problems. However, initial conjectures on the causes of many of these "problems" were misdirected. For example, there was a case where it was alleged that the workmanship was poor where in fact the structure was under-designed. In another case, concrete was accused of not being water-resistant, yet the real culprit was excessive irrigation of the surrounding soil and a lack of adequate drainage.

Of course, there are cases where the concrete itself was not satisfactory for the given conditions in a particular structure. Would it not be better, as well as more economical, to make absolutely sure that the concrete is always "fit for the purpose," in the material itself *and* in the execution of the construction so that the concrete in the structure is accepted unequivocally as such by all involved? In other words, concrete should be tailored to the needs of the designer. But, the designer must know what can be demanded, and that this will truly exist in the finished structure.

Is concrete under threat?

A possible rebuttal of my point of view might be that there is no competitor to concrete in sight. A similar attitude was held by Swiss manufacturers of watches with a mechanical movement. But when Japanese quartz watches arrived, a large number of small Swiss watchmakers disappeared, and highly-skilled personnel became unemployed. There are examples elsewhere, in appliances, autos, and of course computers, to name just a few.

Some changes have occurred principally in design, with consequent alterations in materials. More importantly, there have been cases where evolution in design occurred only when new materials with very specific properties were developed. A striking example is the design of aircraft bodies. Changes there were effected only by using new materials having properties required by the designer. To satisfy this, there developed a kind of symbiosis between the aircraft structural designer and the materials scientist. This has occurred in other fields as well.

In concrete structures, the situation is often that a range of mixtures is available, and designers have to serve themselves from that "menu." Of course, there have been changes in the types of concrete available, but there has been no great progress or dramatic developments. It would be unrealistic to expect changes in concrete comparable to those in the aircraft industry; our industry's structural designers cannot develop new concrete-like materials, and concrete scientists are not in a position to envisage the design changes they could meet. But, the challenge to do better is there, and we need a "brain trust" to find a way forward.

Recent progress

What I have said in the preceding section may not be palatable to some—even many—and I admit that it is a deliberate provocation to galvanize all of us in concrete into action. Of course, there have been changes in concrete and concreting: slipforming, self-compaction, and roller compaction, to name a few. But, what significant overall progress has been made? Air entrainment is now 60 years old, and this was an accidental discovery. Superplasticizers had to wait 30 years until they came to be used in concrete, but undoubtedly they were a very significant development.

The use of concrete mixtures containing a high proportion of fly ash and ground-granulated-blast furnace slag also represents a significant development. There must be other changes that have improved concrete but, overall, concrete construction is, depressingly, much the same as in my younger days. In other words, the changes that have taken place are not as significant as they will need to be to keep out future competition. We should not forget that the consumption of steel has decreased dramatically. Cannot the same happen to concrete as we know it, even though the current use is so huge and widespread?

The future

I dare say it is my advanced age that leads to my pessimism. I may be exaggerating the situation, but my aim is to help jolt the concrete world out of its complacency. What we are doing, I believe, is largely tinkering at the edges. Even the holistic approach is really not much more than another look at concrete as a material, and not at the entirety of the structure, which requires input by the structural engineer.

While this goes on, someone somewhere will find better materials *and* better techniques to build better structures. These materials may include polymers of various kinds as well as all types of fiber components. Portland cement might still be used, but not as the main bulk component of concrete, which at present leads to the frequent problem of shrinkage cracking. It is quite likely that steel reinforcement will no longer be used, thus removing the vexing problem of corrosion.

These are not just flights of fancy. For example, the Department of Mechanical and Aerospace Engineering of the University of Alabama at Huntsville has developed a material composed of portland cement, glass microbeads, latex acrylic fortifier, and water; reinforced with a graphite fiber mesh that can be used for boat hulls, and just 7 mm (1/4 in.) thick, providing strength, flexibility, and crack resistance. Its inventors are looking forward to the use of the new material in spacecraft. This could be an example of symbiosis of structural design and material development. I cannot help observing that, much to my chagrin, it was not in a department of civil engineering where this development occurred. The preceding is, of course, a highly specialized example, but history is full of specialized products being modified in due course into more mundane, widely-used materials.

Moreover, there has been some important development in large structural elements prefabricated to include load-bearing members, internally and externally finished, and connections. This approach provides better overall quality control than traditional construction methods. Specifically, monocoque construction, using composites reinforced with glass fiber, gives great freedom of shape and high durability.

These are not future possibilities: such structures already exist—for example, a five-story building called *Eyecatcher*, built in 1999 in Bâle, Switzerland (described by Thomas Keller in the *Bulletin of the Swiss Association of Engineers and Architects*, September 2001).

These large, innovative elements made of new materials will not be used as a substitute for concrete in structures of the type and form employed at present, which are largely rectilinear and angular. Rather, the direction of development will be to produce more rounded and softer shapes, made possible by the new materials and methods of fabrication and construction. Here, once again, development is a combined change in materials and in design.

My view is, it is the symbiosis of the material specialists and structural designers that is needed. The latter need to know better what is possible with respect to concrete as a material and its processing; the former need to know what is desirable. More mechanization of concreting operations and a greater (than zero) use of robots would undoubtedly improve the uniformity of concrete *in structures*, making them more reliable and, in the long run, more economical.

For us to wait until a “replacement” of “old-fashioned” concrete has arrived is to bury our heads in the sand. For concrete to have a good future, I feel we need a new approach concentrating on the problems I have mentioned. We still have time to find such an approach, but time is not on our side. We have to move more quickly if concrete is to maintain its preeminence as a construction material.

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Selected for reader interest by the editors.

ACI Honorary Member **Adam Neville** has been contributing to *CI* articles on various topics, all aimed at facilitating the use of scientific knowledge to make better concrete in practice. His book, *Properties of Concrete*, first published in 1963 and now in its fourth edition, and translated into 13 languages, has similar objectives. He is a recipient of several awards from ACI and other organizations, as well as Commander of the Order of the British Empire awarded by the Queen for his contribution to science and technology.